Australian Government
Department of Defence
Science and Technology

Acoustic Emission Sensing for Maritime Diesel Engine Performance and Health

Brian Dykas and James Harris

Maritime Division
Defence Science and Technology Group

DST-Group–TN-1486

ABSTRACT

Monitoring and analysis of high frequency acoustic emissions on marine diesel engines may indicate their condition with the aim to increase engine availability and reduce maintenance overheads for the Defence Force. An experimental study was undertaken to evaluate the application of acoustic emission (AE) sensing to the monitoring of both petrol and diesel internal combustion engine operating condition and health. A commercial-off-the-shelf AE monitoring system and a purpose-built data acquisition system were employed in this study, and an array of digital signal processing techniques were drawn from the literature, adapted and applied to this application. Acoustic emission signals from engine-mounted sensors were able to distinguish load conditions and a failing injector, but large increases in big end bearing clearance were not definitely identified from the acoustic emission signals. DST Group recommends that for any subsequent work that the following is considered:

1. Select an overall diagnostic framework (e.g. permanent or temporary, nature of the system being measured, diagnostic method and sensor type),
2. Define a context using a failure modes, effects and criticality analysis (FMECA), and define good AE candidates,
3. Wherever possible characterise AE signatures by constructing simple isolated component test rigs with seeded faults,
4. Apply the technology directly to the engine of interest,
5. Assess the diagnostic performance of various signal processing techniques, and
6. Partner with research institutions with specialist AE knowledge.

Produced by

Maritime Division
Defence Science and Technology Group
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: 1300 333 362
Fax: (03) 9626 7999

May 2016
AR-016-487

Acoustic Emission Sensing for Maritime Diesel Engine Performance and Health

Executive Summary

This work was undertaken to review various current, but novel, commercial off-the-shelf (COTS) diesel engine condition monitoring technologies. It is anticipated that using these technologies would result in improved diesel engine condition monitoring. This would increase engine availability and reduce maintenance overheads for future or existing marine diesels for the Defence Force.

Acoustic emission (AE) monitoring is considered as a potentially valuable novel condition monitoring technique. Acoustic emissions are reported by previous researchers to be produced when engine materials are subjected to external events such as a combustion event, fluid flow or the opening and closing of valves. This document reports on the monitoring and analysis of acoustic emissions in the region of 100 – 500 kHz at various engine locations on a single cylinder petrol and a single cylinder diesel engine. Here we report on the equipment selected, analysis techniques used (within and between engine cycles), difficulties encountered and signals seen when AE technology was used to condition monitor during engine operation. Two AE systems were assessed: firstly an AE COTS system by the Physical Acoustics Corporation (PAC) and secondly a purpose-built system constructed around a National Instruments (NI) PXI data acquisition system.

Initial testing used the petrol engine and the PAC COTS system. This system showed limited usefulness due to built-in system hardware limitations, a low number of input channels, this engine’s high background AE, and considerable crankshaft speed variability. An initial assessment of the same COTS system was undertaken on the diesel engine before progressing to the purpose built NI system for all further work. Baselines were then created by recording normal diesel engine operation at different engine loads. Comparisons were then made with the fault conditions of misfire due to a faulty injector and excessive big end bearing clearance.

The diesel engine, with considerably lower background AE, showed distinct patterns of AE generation in conjunction with injection-combustion processes and valve events. AE from misfire as the result of a fuel injector malfunction was readily detectable. The detection of excess big end bearing clearance up to 0.25 mm was elusive and requires more investigation as the AE systems failed to detect any knock. Of the analysis techniques, the most successful were statistical post processing to show rms residuals (subtracting the baseline AE signal from the misfire signal), co-efficient of variation (detecting cycle-cycle variation size) and autocorrelation (periodicity) of the rms to detect misfire. This work also makes recommendations for future AE investigations.

Overall, AE showed potential to provide non-intrusive monitoring of certain elements of engine operation in the engine top end, but its diagnostic utility would be restricted to only those processes and components that generate detectable and repeatable AE.

DST Group recommends that for any subsequent work that the following is considered:

1. Select an overall diagnostic framework (e.g. permanent or temporary, nature of the system being measured, diagnostic method and sensor type),
2. Define a context using a failure modes, effects and criticality analysis (FMECA), and define good AE candidates,
3. Wherever possible characterise AE signatures by constructing simple isolated component test rigs with seeded faults,
4. Apply the technology directly to the engine of interest,
5. Assess the diagnostic performance of various signal processing techniques, and
6. Partner with research institutions with specialist AE knowledge.

Contents

Acronyms

Acronym	Name
AE	Acoustic Emission
COTS	Commercial Off-the-shelf
DAQ	Data Acquisition
DST Group	Defence Science and Technology Group
FMECA	Failure Modes, Effects and Criticality Analysis
NI	National Instruments
OEM	Original Equipment Manufacturer
PAC	Physical Acoustics Corporation
PXI	PCI eXtensions for Instrumentation
PCI	Peripheral Component Interface
PZT	Lead Zirconate Titanate
rms	Root Mean Square

1. Introduction

To assess the mechanical condition of a powerplant various techniques for measuring vibration have been developed allowing for a near real-time capability for detecting anomalous operation. Vibration measurement has been a common technique for health monitoring of mechanical systems for many decades. Minor defects within high performing components such as gears, bearings and other power transfer devices produce distinct changes in transmitted forces. Such changes may be detected through the resulting structural response. Many signal processing techniques of varying complexity have been developed for improved diagnosis, from simple quantities calculated in the time domain or frequency domain, to more advanced statistical methods incorporating advanced digital signal processing, joint time-frequency methods, and the use of neural networks and fuzzy logic to diagnose condition. For bearing diagnostics, well regarded works include those by Howard [1], Halme and Anderson [2] and Randall and Antoni [3]. For helicopter mechanical systems, an excellent review of vibration-based methods including signal processing approaches is given by Samuel and Pines [4].

Vibration-based mechanical diagnostics have matured in such applications as aerospace power and propulsion as well as stationary mechanical equipment, but are not used in many diesel engine applications. Technology for diesel engine condition monitoring by vibration is usually limited to analysis of single aspects of engine operation with no whole of engine solution yet devised [5]. Examples of single aspect analysis include Armstrong [6] who detected changes in timing and valve clearances using joint time-frequency methods, Liu et al. [7] who detected piston slap using blind source separation methods and Chen and Randall [8] and Chen [9] who applied model-based diagnostics to detect piston slap and bearing knock.

As an alternative to vibration-based diagnostics, acoustic emission (AE) has been proposed as a diagnostic tool for piston engines. Elastic stress waves originating and propagating within a material subjected to external stimulus form the basis of acoustic emission phenomena [10]. These have been studied for several decades especially in the monitoring of material damage in engineering structures. These stress waves travel through solids, interacting with surfaces and many traveling along a solid surface where they can be measured using a piezoelectric sensing element, usually lead zirconate titanate (PZT). Acoustic emissions are produced in discrete packets with the sudden movement of a group of atoms, often referred to as a "burst." When the rate of occurrence of these bursts is high enough that individual bursts can no longer be distinguished, the AE is referred to as "continuous." Unlike lower frequency structural vibration, for our analysis AE is assumed to be characterised by higher frequencies in the 100 - 500 kHz range and more localised in origin and propagation. A very accessible primer on these and other principles of AE is given by Beattie [10].

The application of acoustic emission for diagnosis of reciprocating engines has only been active for about the past fifteen years. Mba and Rao [11] describe the application of AE to an assortment of machinery applications, and Sikorska and Mba [12] highlight some of the practical aspects of measuring AE in these environments, which often differ greatly from

structural health monitoring applications. Appendix A provides an overview of relevant AE diagnostic studies in piston powerplants. As a whole, these studies have shown that analysis of AE measurements on the top end of engines can successfully distinguish operation at different conditions or with various component faults.

This current work was undertaken to assess if this technology and the findings attained by others was able to be replicated and readily applied using easily obtainable commercial off-the-shelf (COTS) equipment to detect common faults (and hence condition monitor) on single cylinder engines, with the intent of assessing it for application to multicylinder marine diesel engines.

The literature shows that some conditions and faults are more readily diagnosed from acoustic emission signals than others, but their versatility and non-intrusiveness combined with relatively low cost make them an attractive sensor for engine monitoring. This report describes preliminary experimental study into the AE diagnostics for piston engines by the DST Group, starting from methods described in the open literature. These methods were applied to small, single cylinder petrol and diesel engines. The validated methods could then be applied to larger and more complex engines more representative of Royal Australian Navy powerplants.

2. Methods

2.1 Data Acquisition Systems

2.1.1 Physical Acoustics Micro-II Digital AE System (COTS AE)

The initial feasibility of AE sensing was conducted using a COTS AE measurement system manufactured by the Physical Acoustics Corporation (MISTRAS Group). The Micro-II AE system was configured with two Peripheral Component Interconnect 2 (PCI-2) AE sampling cards, providing a total of four (4) 18-bit channels of high speed input (up to 10^7 Samples/sec streaming to disk) as shown in Figure 1. The PCI-2 high speed inputs are configured with built in filtering and amplification, and provide direct current power to the preamplifier over the signal BNC cables. These preamplifiers are reasonably compact, and some PZT sensors are available with built-in preamplifiers to further simplify the installation. The Original Equipment Manufacturer (OEM) provided AEWin software provides an interface to the device for data recording and basic analysis.

While COTS AE systems such as this are in common use especially for structural health monitoring applications, there are some limitations when the system is used for dynamic machinery monitoring. These limitations primarily arise when signals other than AE (e.g. crank position) need to be synchronously recorded with the AE. Furthermore, while the software has been developed quite extensively for burst emissions, these features did not extend well to the signal processing for engine monitoring, so raw signals were recorded to disk and these signals were then post-processed in Matlab.

In summary the COTS AE system attributes are:

- This system is a good compact acquisition system and relatively easy to set up;
- Good especially when only AE signals are of concern and with low channel counts;
- Designed for structural health monitoring where counting and triangulation of burst emissions is the objective, but engine studies rely more heavily on continuous waveform characteristics over the crank cycle;
- Good for high speed data acquisition system of a small number of AE channels, but channel count can be limited when other signals such as the tachometer and encoder need to be simultaneously sampled; and
- Cannot bypass the integrated highpass filter, so cannot record DC signal values.

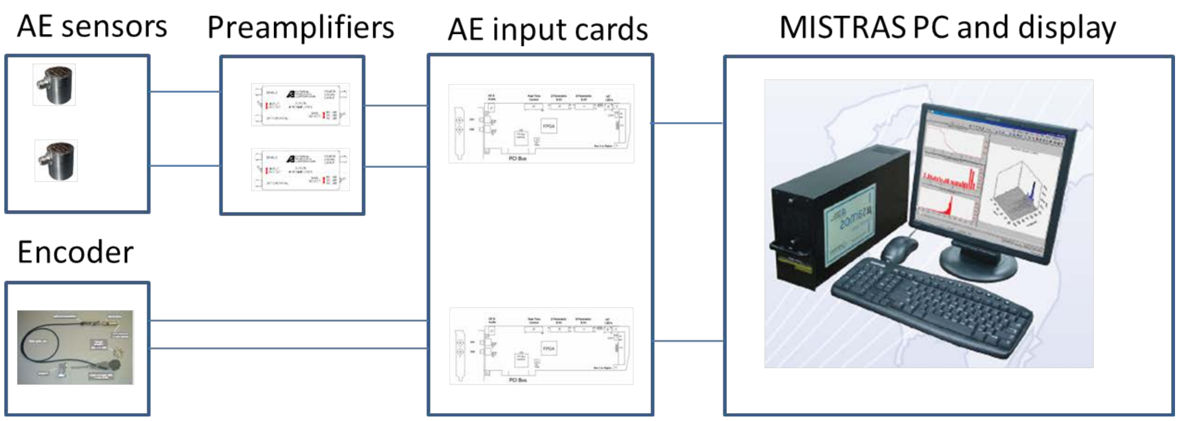


Figure 1 COTS AE measurement system

2.1.2 National Instruments PXI-based Data Acquisition (Custom) System

To improve the flexibility and channel count for the AE measurements, a second system was assembled based on the lessons learned using the COTS approach. The PCI extensions for Instrumentation (PXI) hardware platform and accompanying Labview software environment available from National Instruments Corporation provide a high speed data acquisition platform common in test and measurement applications across many industries. A PXIe-6366 X-Series multifunction data acquisition (DAQ) card provides eight (8) 16-bit analog inputs that can be sampled at a maximum of 2 MSamples/sec simultaneously, but this system can be scaled with additional input cards to allow additional channels as needed. The basic data acquisition hardware is shown in Figure 2.

The same PZT AE sensors used in conjunction with the COTS system were compatible with this custom system. However, since this data acquisition system does not provide direct current power to the preamplifier, equivalent pre-amplifiers with external power inputs were purchased, but the filtering and gain properties remained the same. The data acquisition card does not incorporate the specialised filtering and amplification of the COTS system, instead requiring any signal manipulation to be performed on the sampled digital signal. As a flexible "expert" system, it requires more setup and expertise than the COTS system.

The Custom System has the following attributes:

- The PXI and Labview (National Instruments) products it employs are common in the test and measurement industry, well documented and understood by many test engineers;
- More channels to incorporate other instrumentation easily;
- Scalable and flexible;
- Provides additional control over filtering/signal conditioning enables parametric study and optimisation;
- Not as compact as COTS system, wiring and software configuration are more complex and require operator familiarity; and
- Possibly prone to noise or signal issues without the specialized AE analogue circuitry.

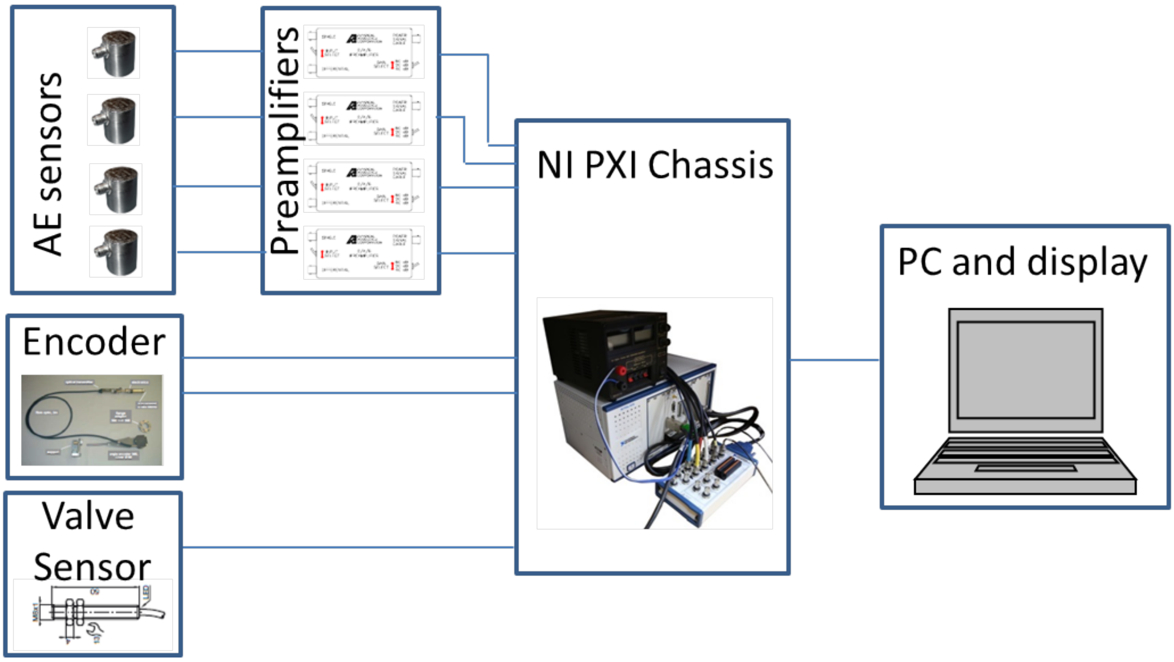


Figure 2 Custom High Speed Data Acquisition System

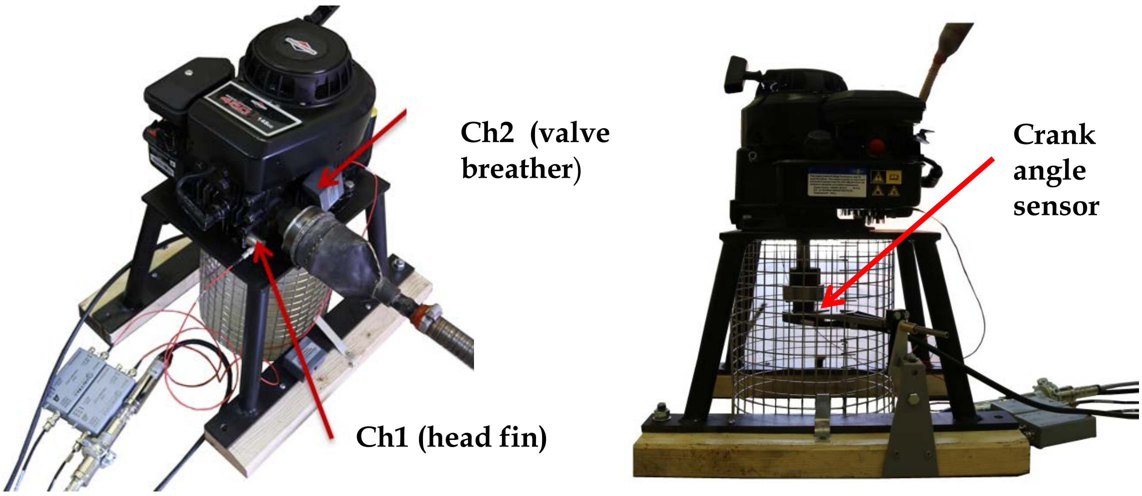
2.1.3 Sensors and Preamplifier Selection

A significant number of different sensors are available to detect AE in various frequency ranges. Here, our selection mimicked those commonly used in other studies. The F15α passive wideband sensor has a reasonably flat frequency response from 100 – 450 kHz. The micro-80D is a general purpose miniature sensor with a rated frequency range from 175 kHz-900 kHz and a resonant frequency around 325 kHz. The sensors were connected either to PAC 2/4/6 preamplifiers (used with Micro-II data acquisition) or PAC 2/4/6C preamplifiers (used with PXIe-6366 data acquisition) with an integral bandpass filter from 20-1200 kHz and each having a selectable net gain of +20, +40 or +60 dB.

2.2 Engines

2.2.1 Single Cylinder Spark Ignition Engine

Initial trials were conducted on a single cylinder, spark-ignited Briggs and Stratton 450 series engine shown in Figure 3. It is a four-stroke engine with a displacement of 148cc and nominal operating speed of 3600 rpm and an output power of approximately 1.7 kW (2.3 hp). Engine speed is governed through an aerodynamic-mechanical mechanism. This engine provided a simplified environment for validation of sensor measurements and methodologies. With only a single cylinder, it is easier to identify events such as valve opening and closing in the crank domain without contributions from mechanical events in other cylinders. It also provides a simplified structure without complex mechanical and accessory systems, cooling arrangements, and other complexities of larger engines. The COTS AE measurement system was used with this research engine, with only two acoustic emission signals able to be recorded in addition to the tachometer and encoder signals. The first AE sensor was bonded on a cooling fin on the cylinder head, and a second was placed with a magnetic mount to the valve breather (adjacent to the cam followers) on the side of the engine, as shown in Figure 3. The preliminary tests of the small spark ignition engine focused on developing data collection methods and verifying methods used in the literature.



(a) (b)

Figure 3(a) and (b) Single Cylinder Gasoline Engine showing AE and crank angle sensors

2.2.2 Single Cylinder Diesel Engine

Following the trials on the single cylinder spark-ignition engine, application of the acoustic emission sensing was applied to a small single cylinder compression-ignition (diesel) engine, shown in Figure 4. The Yanmar L100N5 engine is rated at 5.7 kW continuous/6.5 kW maximum at 3000 rpm and is coupled with a Powerlight PYD070E generator. The generator is rated to a maximum 6.0 KW at 3000 rpm with a power factor of 1.0, and a nameplate output of 240VAC /50Hz up to 24A. The engine has a displacement of 0.435 L.

Like the smaller spark-ignition engine, this engine provides a reasonably simple testbed for experimental measurements without more complex dynamic response and interaction of multiple cylinders. In addition to valve events, mechanical systems associated with the piston-crank system are similar in nature to the spark-ignited engine with the carburettor and magneto ignition replaced by a fuel-injection system. In the diesel engine the compression ratio is higher and at approximately 15 m/s the maximum piston velocity is slightly higher in than the spark-ignited engine. Generator loads of 0 kW, 2 kW and 4 kW were accomplished by switching one or two 2.0 kW Fanmaster IFH-2 portable electric heaters, which covered a range of 0-67% of the generator's rated load.

Although some initial experiments on the diesel were conducted with the COTS AE measurement system, most data were sampled using the purpose-built measurement system to allow recording of additional channels of instrumentation. Four channels of AE were recorded from the diesel engine and listed below in Table 1 and pictured in Figure 4. Later experiments exploring bottom end faults substituted one of the sensor locations.

Table 1 AE sensor locations

Channel	Location
1	Inlet Manifold
2	Injector Retainer
3	Fuel Tank Stay
4a	Fuel Injector Pump
4b	Crankcase Cover

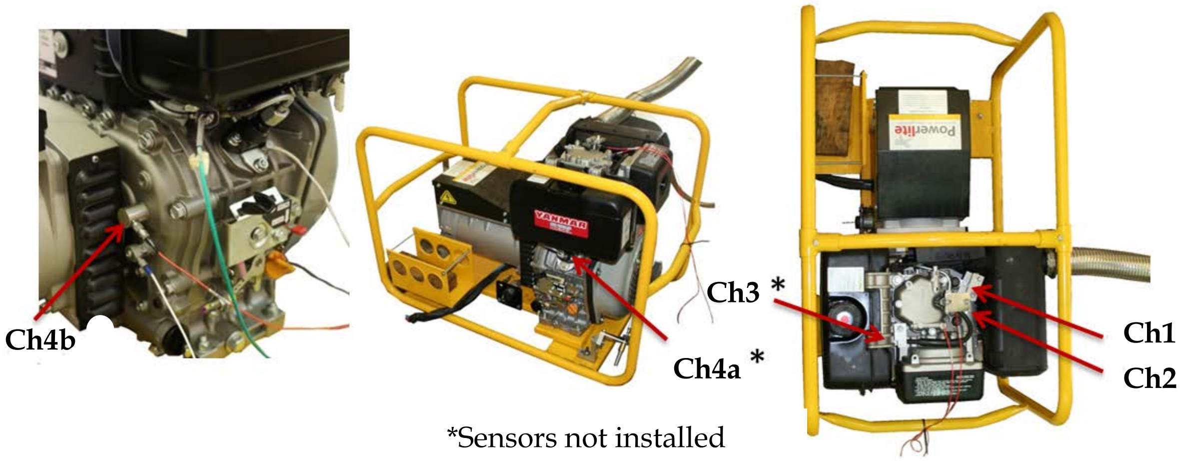


Figure 4 Single Cylinder Diesel Engine and Generator with Sensor Locations

2.3 Signal Processing

2.3.1 Raw AE signals

The time domain acoustic emission signals were generally recorded at 2 MHz, with a corresponding Nyquist frequency of 1 MHz. With the F15a and micro-80D sensor responses limited to 450 and 900 kHz, respectively, and little signal content above 500 kHz, this sample rate was adequate for the application. The tachometer signal and a high resolution encoder signal are sampled simultaneously to allow for accurate phase (crank angle) information to be derived.

The raw signals are characterised by regions of relatively low signal energy, interrupted by regions containing large packets of continuous mode AE where multiple AE bursts appear to overlap and are not clearly distinguishable from one another, as shown in Figure 5. Since the signal processing features of most conventional AE measurement systems are more heavily focused on signal characteristics associated with burst emissions, the capture of raw AE signals in the time domain and custom-developed digital signal processing code were required for this work.

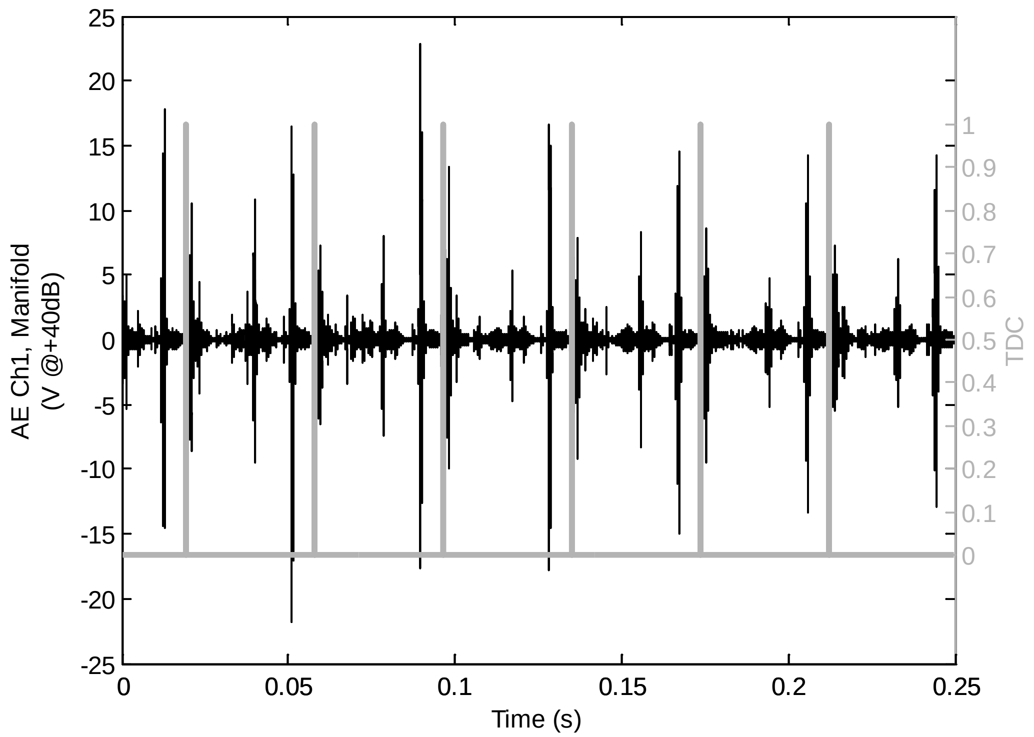


Figure 5 Raw AE signal for 1-cyl diesel at 0 kW, with top dead center reference signal

2.3.2 Instantaneous Root Mean Square (rms) AE

The most common method of analysing the continuous mode AE measured in engine applications is to first calculate an instantaneous root mean square of the signal using a time constant in the range of 20-200 µs. This gives a measure of the local waveform intensity or energy and allows for downsampling to much longer sampling intervals, often reducing the volume of data by a factor of 10-100.

The periodicity of the raw AE signal in this study was interrogated using the autocorrelation function, a common technique in digital signal processing. This showed only weak evidence of periodicity. This could be attributed to the random and stochastic nature of the individual AE bursts. However, the same autocorrelation operation applied to the corresponding rms AE signal shows clear periodicity associated with the crank cycle, and this could also highlight variability between cycles. This implies that an accurate phase reference signal is not required, as the rms signal changes much more slowly than the raw AE signal. The importance of this result is discussed in Section 4.1.

2.3.3 Synchronous Averaging

At each discrete angular location over the full 720° of crank, the rms acoustic emission signals were averaged for all rotations to obtain a mean signal. Calculation of this ensemble average of a signal is a common technique in machinery applications to enhance signal to noise ratio and to de-emphasise signal components not synchronous with the rotating machinery.

Plotting the averaged rms acoustic emission in the crank domain for each sensor provides insight into the source of the AE activity when compared to the known positions of various engine events such as valve actions, injection, etc. For each operating condition these average rms AE signals are used to establish a baseline signal. New observations can be compared to an appropriate baseline using a variety of change detection algorithms. One tool used the synchronous averaged rms AE signal subtracted from a relevant baseline to form a residual signal. Any localised, significant excursions in the residual signal can be useful to identify an abnormal process or component within the crank cycle. It was found that residuals as a result of synchronous averaging could be readily obtained but causes for change to these residual signals were unable to be directly related to any condition. They may relate to multiple simultaneous changes within the engine environment due to both its long term mechanical condition (i.e. state of wear) and immediate operating condition (e.g. temperature dependant clearances, fluid flows, state of combustion). More investigation would be necessary with isolation of each fundamental variable before its value as a condition monitoring tool was ascertained.

2.3.4 Statistical Properties

In addition to the synchronous average of each acoustic emission signal over the crank angle domain, dispersion properties of AE signals from cycle to cycle were also considered. Standard deviation and variance, maximum and minimum values of the AE

signal at a given crank angle were drawn from the population formed by all rotations in the data record.

Portions of the acoustic emission signals exhibiting abnormally high dispersion properties could be used to highlight particularly variable processes or departure from normal operation. Higher order statistics of these populations (such as skewness and kurtosis) might also be analysed in change detection algorithms, but were not considered in depth for this preliminary work and represents possible future investigation.

Statistical properties of populations can be used in conjunction with other signals and data derived from the raw AE signals. Any future selection of statistical operation and operand requires careful consideration and insight in order to achieve any level of diagnostic effectiveness, so this preliminary work developed and considered only a few parameters in exercising the initial tools and the results are shown in Section 3.2.2.

2.3.5 Spectral Methods

In dynamic machinery the complex environment is thought to create broadband AE from which little information can be gained from spectral analysis [13]. Various AE sources interact with the complex geometry and interfaces resulting in wave conversion. As a result, most reported studies of engine AE diagnostics ignore spectral content and immediately process the AE into an instantaneous RMS and downsample it.

For this exploratory work however, the spectral content was preserved and examined in a few different contexts to determine whether it can be diagnostically useful, including:

1. *Frequency content of overall signal*. Taking the discrete Fourier transform of the raw AE signals shows where the signal energy is concentrated. This can be helpful for the selection of wideband or resonant sensors appropriate to the signal.

2. *Frequency content as a function of crank angle*. At different points in the crank cycle the AE source mechanisms and the wave transmission and conversion aspects will vary. Scripts were developed to show the short time Fourier transform (or spectrogram) in the crank domain. Some differences in the frequency distributions were observed for different sensor locations and source mechanisms, but the data were insufficient to draw strong conclusions in these small engine trials.

3. *Shift in spectral content under fault conditions.* It was hypothesised that the introduction of a fault condition might cause a shift in the observed frequency of AE, depending on the source phenomenon and location. Because of the complex environment and stochastic nature of the observed AE, the feasibility of techniques such as this may be highly dependent on fault mode, geometry, and other specific attributes. Here again there was insufficient scope to provide enough data to draw strong conclusions.

Several algorithms and visual tools were developed in this work for the investigation of the spectral content of AE as described above, but the limited scope of this initial review

prevents the drawing of any strong conclusions from the data. It is expected that the application of these tools as secondary instrumentation on other trial runs may provide additional insight over time.

3. Results

3.1 Spark Ignition Engine

Due to constraints associated with the COTS AE system only relatively short data records of approximately 128 ms duration could be sampled. For the spark ignition engine this period represented only 4 - 5 crank cycles. Figure 6 shows such a 128 ms record with crankshaft speed varying significantly from crankshaft cycle to cycle (0 – 720°). High resolution angle data from the attached encoder did however preserve accurate angle information irrespective of this speed variation.

Figure 7 shows the rms acoustic emission for each signal after it has been indexed and averaged in the crank domain over multiple cycles to de-noise the signal. There are a number of notable features of the broadband rms acoustic emission on this plot. Firstly, the sensor on the head fin measures a background level of AE over the entire crank cycle that amounted to approximately 30% of the peak signal value. This unexpectedly high level makes it difficult to discern individual source events. This result may be attributed to the compact engine size and the proximity of the head fin to most top end sources of AE including combustion, ring-cylinder contact, flow, and impacts associated with the intake and exhaust valves.

The AE from the valve breather sensor does not contain such high levels of background AE, with clearly identifiable peaks seen rising from minimal background AE levels. The valve breather sensor location has some separation from some potential AE sources associated with the head, which may help to explain the lower background noise. Peaks in the signal from this sensor are consistent with the timing of the opening and closure of the intake and exhaust valves. This was expected due to its proximity to the valves and cam followers.

In attempting to measure spark and combustion, the spark was determined by static measurement of the magneto components to have been generated at around 30 degrees before top dead center (direct measurements of magneto voltage while operating were not made). The detection of AE associated with this spark and the subsequent combustion was not detected - which was an unexpected result. It is reported in the open literature that in a diesel engine the heat release of combustion was shown to correlate with higher levels of AE [14].

It is unclear if such heat release was masked by the continuing noise seen at the head fin. The large amount of signal noise on the head, as well as limitations in sensor placement given the cooling fins and shrouds limited the preliminary trials on the spark ignited

engine. Some parametric investigation was conducted on the effect of choosing various filter cut-off frequency settings from those available on the analogue input channels. Within the rated range of the sensor this had little effect on the resulting rms AE signals, which reinforced the notion that the rms AE response is generally not strongly dependent on filter ranges.

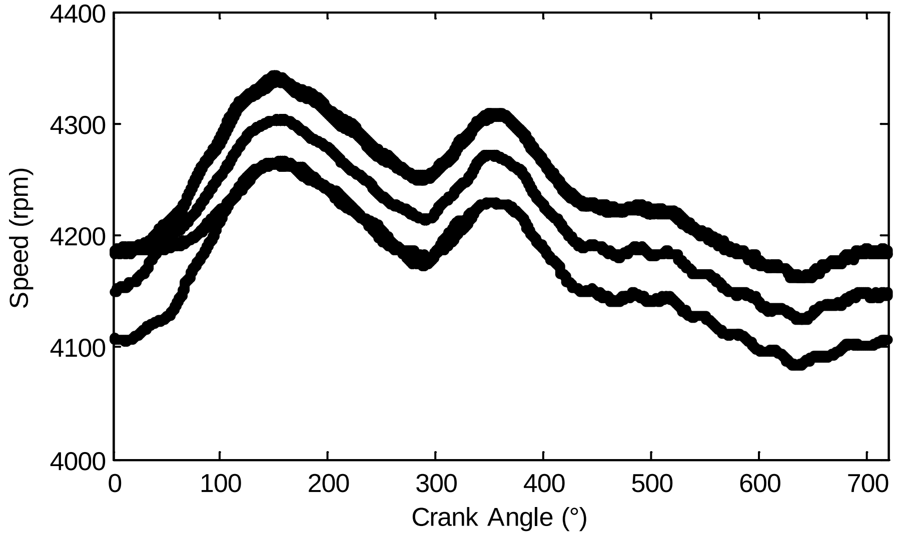


Figure 6 Speed variation for spark ignition engine (128 ms record only)

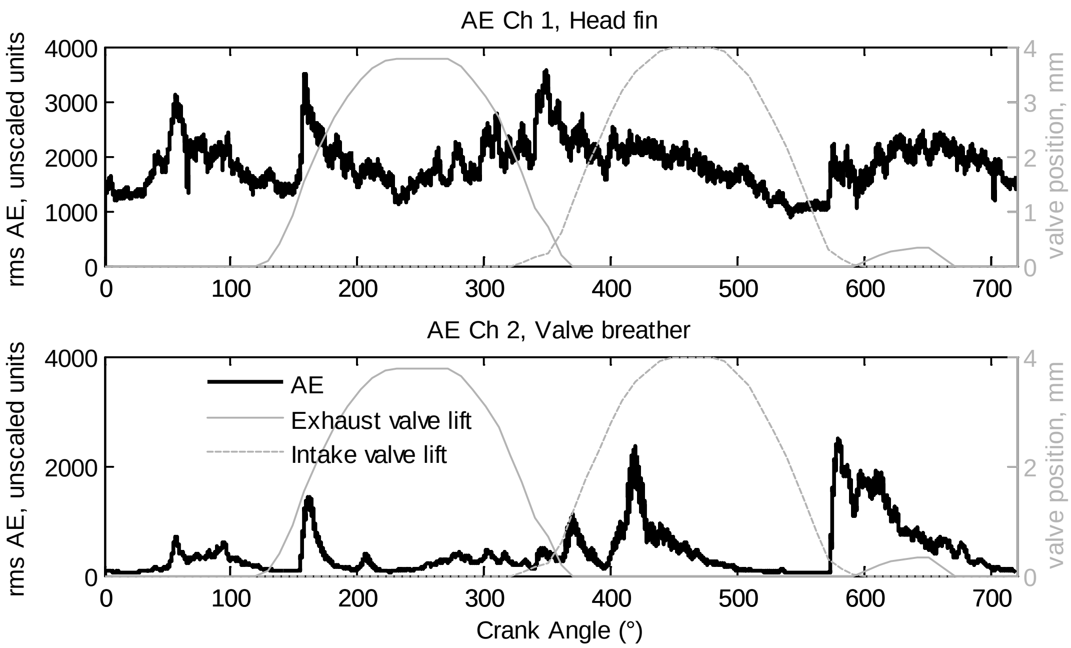


Figure 7 Averaged rms AE over crank cycle, shown with normalised piston and valve positions

3.2 Diesel Engine

3.2.1 Normal Operating Conditions

Figure 8 shows the single cylinder diesel engine crankshaft speed. In comparing the speeds shown in Figures 6 and 8 it can be seen that the diesel engine produced a much more consistent and repeatable engine speed than that of the petrol engine. It is anticipated that multi-cylinder engines would ensure an even more steady and repeatable speed signal. All AE signals from the diesel engine showed low background noise levels when compared to the petrol engine. Figure 9 shows the averaged response of all four sensors in the crank domain, along with the position of the valves. The fuel injection process is easily seen in the AE signal with a rise beginning about 20° before top dead centre with the strongest response measured by sensors on the fuel injector retainer and fuel pump. AE activity also appears to be associated with valve opening and closure events, with all sensors registering these events though the manifold and fuel tank stay sensors respond much more strongly. Similar signature was also seen at the valve breather of the petrol engine. Such events may be associated with throttled gas flow but was not validated as part of this work.

Among multiple measurements at a given condition it is noted that there was some variability in the magnitude of the signal between runs at different times or days. This made simple direct deterministic comparison of events to a baseline an ineffective diagnostic tool. This was attributed to the stochastic nature of the generation and transmission mechanisms, as well as some variability in the physical processes themselves, such as combustion and the effect of removing and replacing AE sensors. It was also found that the synchronous averaged AE signals at a given condition were more repeatable when the engine was under load than when it was unloaded. In Figure 9, at the highest load tested, the both inlet and exhaust valve opening and exhaust valve closing appeared to generate the most distinguishable AE and was detected best at the manifold and fuel tank stay - directly adjacent to the combustion chamber. Therefore, the load on the engine could be readily distinguished from this feature in the AE signals, a potentially useful diagnostic feature.

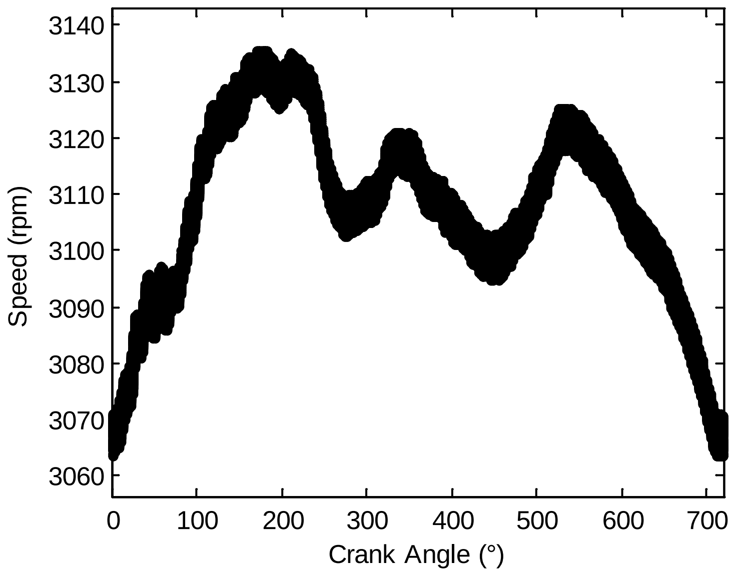


Figure 8 Speed variation for diesel engine over 1 second of data record

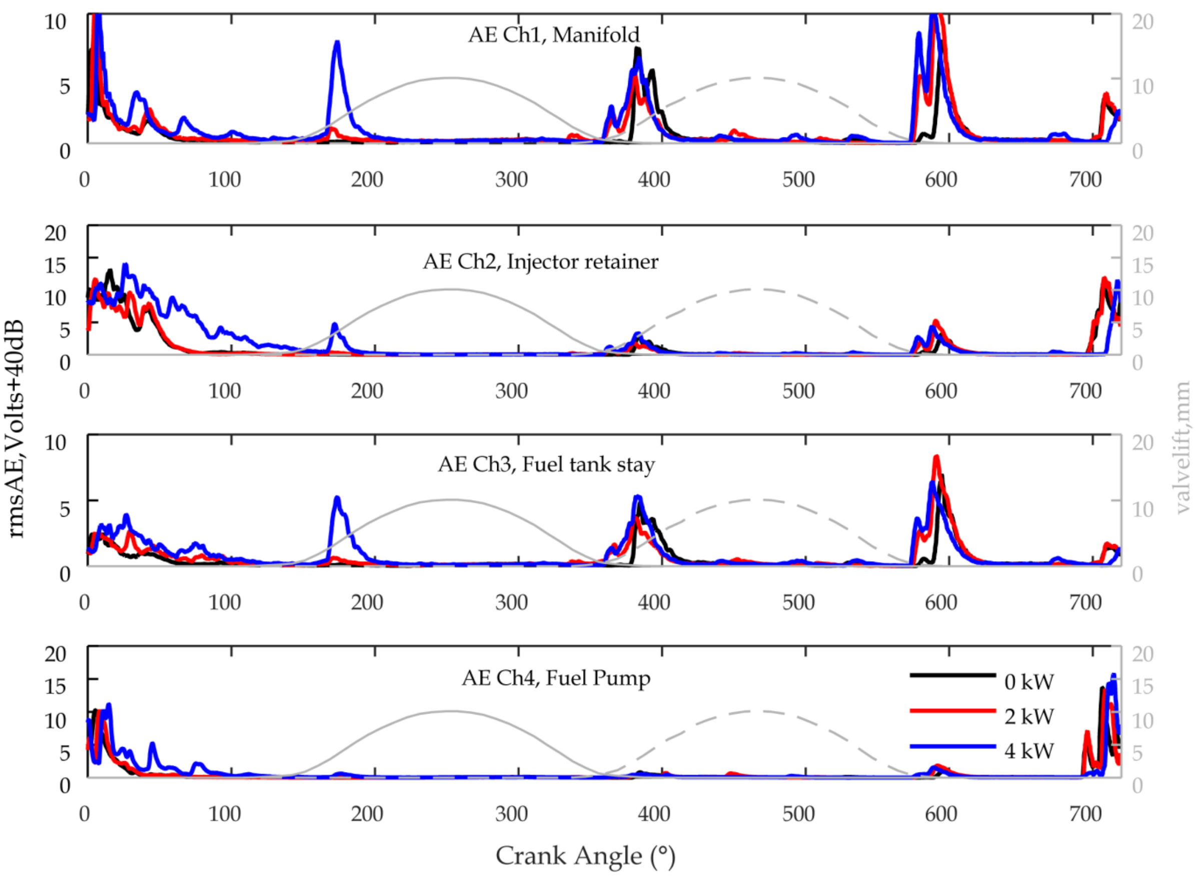


Figure 9 Rms AE signals from diesel engine with valve positions in crank domain (exhaust solid, intake dashed)

3.2.2 Misfire

During the course of trials, a fault developed serendipitously wherein the injector became fouled and the engine began to misfire. During the initial stages where operation was mostly maintained at the governed speed of approximately 3000 rpm, the failing injector condition was first noted as an audible change, along with some visible traces of smoke. The generator was unloaded, several data snapshots were taken for analysis, and then the engine was then quickly shut down to prevent damage. Subsequent start-up resulted in rough running at low speed and at this point the injector was removed for examination. On subsequent "pop" testing the injector plunger was found to be fouled and partially stuck open, leading to over-fuelling and poor cycle timing.

Analysing the tachometer signal only during the misfire, it was apparent that although the average speed remained very near its nominal value, there was a substantial increase in the cycle-to-cycle variation, though the variation was still bounded within about 1%, possibly a valuable condition monitoring metric - though it would be less prevalent on a multicylinder engine.

Three distinct techniques applied to the AE signal detected change between the normal condition and the recorded misfiring condition:

1. *Rms AE residuals signal*. This is a measure of difference between the baseline and the AE rms signal at misfire: This residual signal was constructed by subtracting baseline rms AE signals across the whole cycle from the AE during misfire. For all sensors, this metric was effective in distinguishing the misfiring condition against load-specific baseline signals. A comparison of the normalised residual rms metric across all sensors and conditions is given in Figure 10.

2. *Coefficient of variation.* This is a measure of signal dispersion: A coefficient of variation metric (normalized standard deviation) across all cycles in a data record was computed; the misfiring condition was able to be distinguished on the injector and fuel pump AE signals using this metric. The AE activity on those sensors had an unusually high degree of cycle-to-cycle variability when misfiring, as might be expected. This metric does not require a point-wise comparison of the AE signal to a baseline, rather it calculates a single-valued statistical dispersion parameter of the current signal. A further advantage of this was that the baseline values were similar in value for each operating condition, which would simplify threshold setting and interpretation. Figure 11 shows the elevated variation in the AE signals from the injector (AE Ch2) and fuel pump (AE Ch4), although the manifold sensor (AE Ch1) did not clearly distinguish it, and the fuel tank stay sensor signal (AE Ch3) became unreliable late in the test and was discarded.

3. *Autocorrelation of rms AE*. This is a measure of the periodicity (repeatability) of the signal. Applying the autocorrelation function to rms AE measurements was used to quantify the repeating pattern in the signal. Using this technique the periodicity with crank cycle was clearly seen, illustrated by the local maxima linearly decaying from the centroid of the data to the ends of the data record. The same operation on

the misfire condition results in much more variable decay of the peaks, with this comparison shown in Figure 12. This effect results from the variability among crank cycle periods as the speed changes slightly. This signal attribute is quite obvious for this condition in a single cylinder engine but it may be undetectable in an engine with only one of many cylinders misfiring, so its value in multicylinder engines would have to be assessed separately.

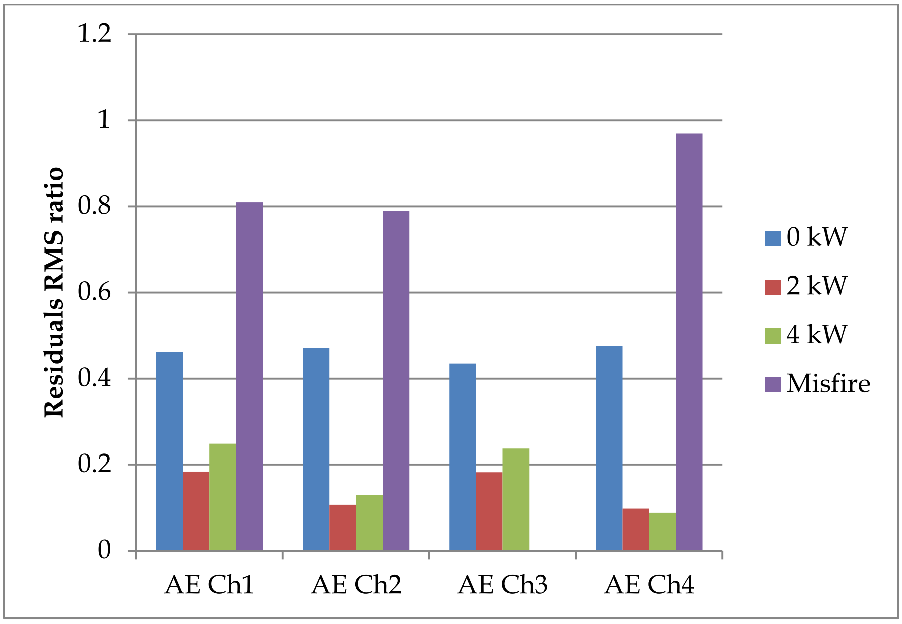


Figure 10 Overall rms of residuals signals, normalised by average rms of two signals compared

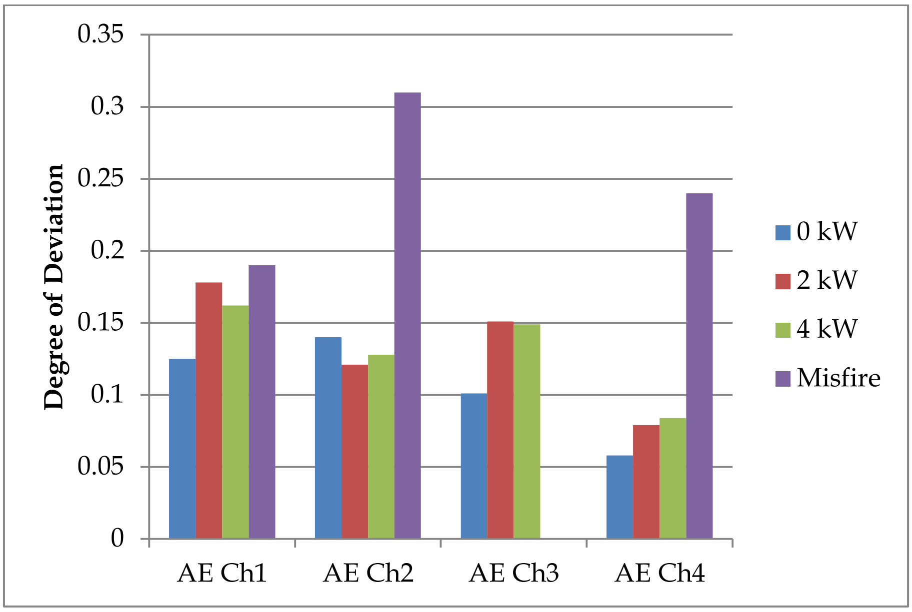


Figure 11 Average coefficient of variation for rms AE signals

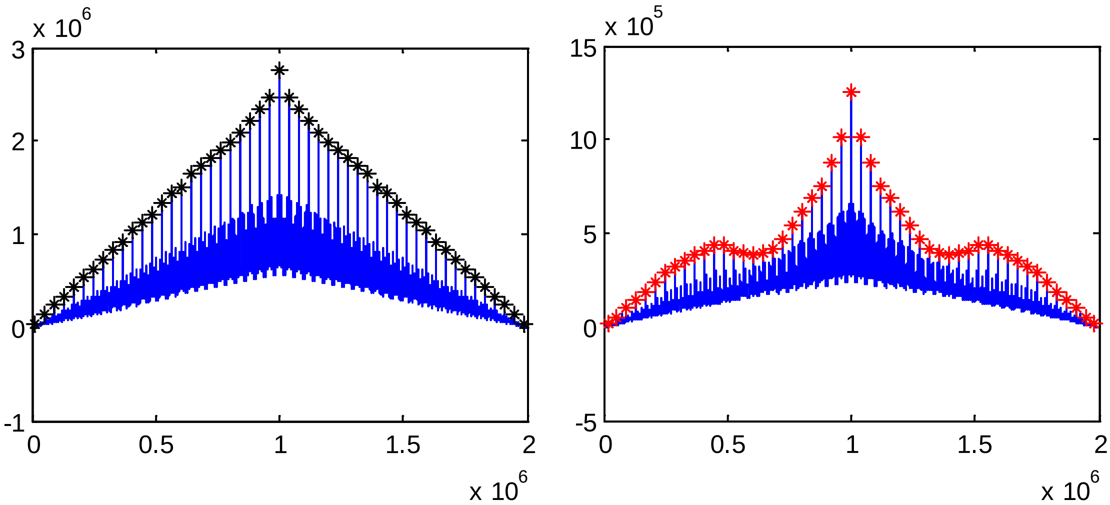


Figure 12 Autocorrelation of rms AE signal for (left) normally functioning engine and (right) misfiring engine

3.2.3 Big End Knock

Although the open literature describes success in applying acoustic emission diagnostics to detect top end phenomena and processes as described in Appendix A, there is virtually no published work describing the use of these techniques for the detection and diagnosis of bottom end phenomena associated with the crankshaft and associated mechanical systems. The current work included a set of seeded fault experiments simulating excessive

clearance within the crankshaft-connecting rod journal bearing, a condition also known as “big end knock.”

As the clearance between the connecting rod big end bearing and journal increases, vibration and noise can increase substantially as the journal and bearing impact repeatedly during the reversing motion of the piston. This condition can ultimately lead to oil film rupture bearing shell wear and failure of the engine. Figure 13 shows a diagram of the connecting rod and piston assembly with the big end bearing shells called out.

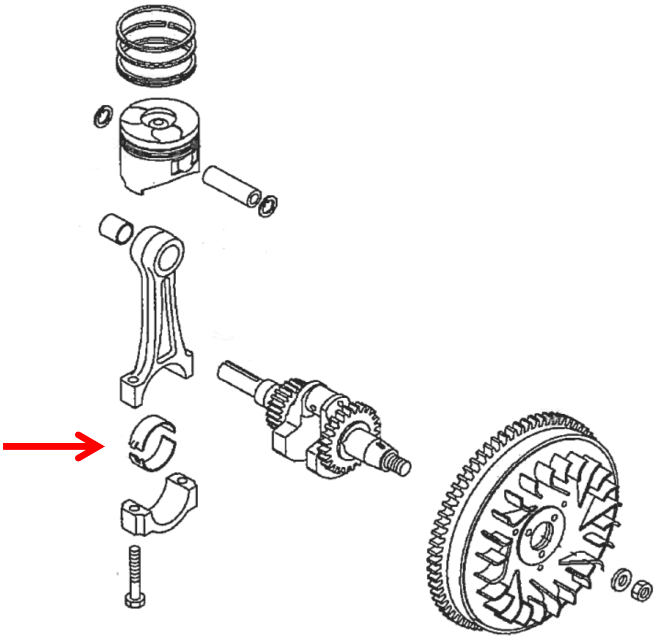


Figure 13 Diagram of connecting rod assembly with the bearing shells indicated (68, 70)

The nominal clearance for this big end bearing is 0.05 mm; in addition to running the normal clearance, three other clearances were run – 0.10, 0.18, and 0.25 mm. These cases of excess clearance thus correspond to 2x, 3.5x and 5x the normal clearance for this bearing, which would generally be considered quite a severe amount of wear on a bearing of this type and size.

Comparison of the synchronous averaged rms AE signals obtained even at maximum clearance to those at the normal clearance did not show clear changes in the AE signals. There was absence of change to AE near piston reversals, where the kinematic motion and piston forces might be expected to cause impulsive/impact forcing. The absence of AE signals specific to these regions suggests that the either the condition is causing little to no AE activity or is not being transferred to any sensor location. In either case the signal to noise ratio may be so poor that it cannot be practically diagnosed using these methods and sensors.

In order to measure AE at the bottom end sensor locations, any AE generated within the bearing would have be transferred through fluid film interfaces including the crankshaft main bearing to the crankcase cover or through the gudgeon pin interface and piston rings

to the cylinder wall . These fluid film interfaces are expected to be poor transfer paths for AE due to the impedance mismatch at the fluid/solid interfaces.

There was evidence of some, though minimal, contact wear on the bearing shells shown in Figure 14. We could not distinguish whether this was the result of an initial break-in and transient start-up phenomenon or as a result of a continuous impact process that should have been measurable in AE and combined with AE from the flow of lubricant or intermittent contact between the bearing and journal solid surfaces.

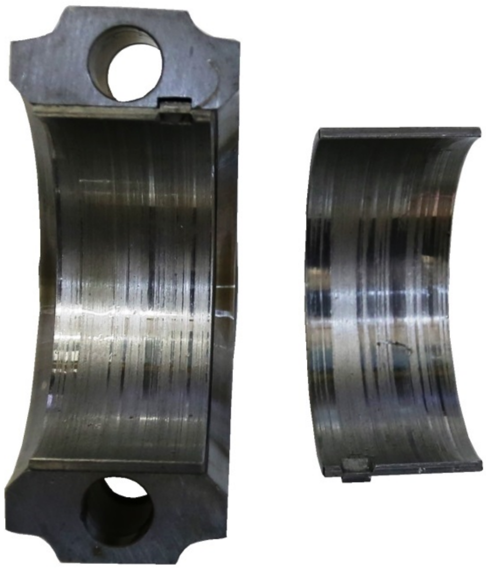


Figure 14 Bearing shells after trials showing polishing wear (0.18 mm clearance)

As such, the lack of clear success in diagnosing the increased clearance condition with AE is not entirely discouraging. Analysis of signals from multiple accelerometers and a high frequency microphone also failed to distinguish reliably between the clearance conditions using commonly accepted methods of diagnosis such as envelope analysis.

4. Discussion and Conclusion

4.1 RMS Measurement

As discussed in Section 2.3.2 the most common method of analysing the continuous mode AE from the engine was to first calculate an instantaneous root mean square of the signal using a time constant in the range of 20-200 μs. The processing of this raw AE was demanding with the AE itself being of random and stochastic bursts but with the corresponding rms AE signal showing clear periodicity and corresponding reduction of data volume by a factor of 10 to 100. This is a powerful finding as on this basis future

measurement of AE could be best done by the provision of sensors that internally process AE and have only an rms output. During the duration of this study rms sensors were made available to the commercial market by PAC. The availability of this PAC R15-ASL sensor would allow any future work AE to be undertaken at drastically reduced rate (from MHz to tens of kHz) using a sensor compatible with existing commercially available electronic hardware.

4.2 Assessment of Acoustic Emission Monitoring Equipment

The PAC system though an integral COTS system and its software demonstrated that it had limitations in monitoring dynamic machinery (having been developed extensively for the monitoring of structures and burst type transmissions) and possessed a limited number of inputs. It also had a high bypass filter so could not record DC signal values. The application of the custom National Instruments PXI system using the PAC AE sensors and preamplifiers and post processing using Matlab adequately recorded and analysed the AE associated with internal engine events.

4.3 Petrol Engine

For the petrol engine trials:

- Engine processes for this single cylinder gasoline engine had a large degree of variability in engine speed and background AE making it difficult to draw strong conclusions;
- Valve closing events are evident in rms AE signals but only measured at the valve breather - it is probable that like a wave type phenomenon AE is affected by the distance from the source and the nature of transmission path;
- Broadband AE measurements on the cylinder head did not reveal high levels of AE corresponding to the heat release of combustion, as has been reported previously in the literature, possibly due to high levels of noise and low signature levels; and
- Deconstruction of the AE signals into spectral components did not show immediate and obvious trends for various engine processes.

Overall the single cylinder petrol engine was limited in its direct contribution to the study of AE but demonstrated the limitations of the COTS AE system and allowed development of several analysis techniques which were then applied to the diesel engine.

4.4 Diesel Engine

For the diesel engine:

- When compared with the single cylinder gasoline engine, AE sensors measured far lower background levels in the acoustic emission signal throughout the crank cycle;

- All sensors appeared to respond to events from both combustion-ignition and valve closure/flow, but at varying relative levels according to the proximity of the sensor to the source, and transmission path;
- The strong AE signal components associated with exhaust valve closure is promising for maritime applications. A study of surface ship reliability has highlighted exhaust valves as being responsible for 27% of main engine faults in the recent past [15] demonstrating the potential of this individual signature;
- For the misfiring injector, three distinct analysis methods on the AE signals were able to distinguish the condition, including comparison of rms AE signal to a baseline, cycle-to-cycle variance within the signal, and autocorrelation to diagnose periodicity; and
- For the condition of increased big end bearing clearance, AE could not conclusively diagnose the condition even in the most severe case. Vibration and airborne acoustic measurements also failed to conclusively diagnose the condition, so the severity of the fault could not be verified.

Overall the significant finding here is that for diesel engines AE was able to detect the presence of engine misfires and show promise in the detection of exhaust valve operation. Hence AE was able to detect numerous top end conditions.

It was also important to note that the apparatus did not detect excessive big end clearance. Given the lack of a distinct big end bearing clearance AE signature, better research of AE sensing for this fault would be undertaken by simulating it on a component rig rather than a full engine. The simplified mechanical environment and better control over operating condition and forces would permit a more objective evaluation of the potential for AE to diagnose this condition. Conversely as with previous researchers AE was able to detect some engine “top end” processes.

5. Recommendations

This initial work was exploratory in nature. Based on these results, any further investigation of acoustic emissions should be more specifically targeted. And given that the study here has shown that certain components or processes can be successfully monitored more targeted study would be required. We recommend that any subsequent study consider the following:

1. *Choose diagnostic framework.* Determine if the proposed diagnostic system, is permanent or temporary, the frequency of measurement, the steadiness and certainty of the operating condition, the quantity and type of sensors, and the methods used to diagnose from sensor inputs.
2. *Application context for AE diagnostics.* Consider acoustic emissions diagnostics in the context of a FMECA or similar. Prioritise where AE may be a strong candidate to provide information more effectively than other options.

3. *Component test.* Whenever possible, construct simple component test rigs to evaluate the AE signatures of operating components of interest and with seeded faults. Repeatability effects associated with sensor installations or adjustment would also need to be characterised in component test.
4. *Experiment on a relevant engine.* The intended application of this sensing technology to large multi-cylinder diesel engines introduces large challenges in scaling. Trials would be needed on that engine and would also need to characterise the measurement variability over long periods of time.
5. *Parametric study.* There is little in the literature assessing the relative diagnostic performance of various signal processing techniques. Signal processing parameters, sensor sensitivity, filter cut-offs, time constants, and similar parameters must be assessed to optimise signal processing algorithms.
6. *Engage academia.* Particularly in the further refinement of digital signal processing techniques and interpretation of data, partnering with academic institutions with specialist knowledge is recommended.

6. References

1. Howard, I. (1994) *A Review of Rolling Element Bearing Vibration'Detection, Diagnosis and Prognosis'*. DSTO-RR-0013, Defence Science and Technology Organisation
2. Halme, J. and Andersson, P. (2010) Rolling contact fatigue and wear fundamentals for rolling bearing diagnostics-state of the art. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* **224** (4) 377-393
3. Randall, R. B. and Antoni, J. (2011) Rolling element bearing diagnostics—A tutorial. *Mechanical Systems and Signal Processing* **25** (2) 485-520
4. Samuel, P. D. and Pines, D. J. (2005) A review of vibration-based techniques for helicopter transmission diagnostics. *Journal of Sound and Vibration* **282** (1–2) 4/6/ 475-508
5. Randall, R. B. (2011) *Vibration-based condition monitoring: industrial, aerospace and automotive applications*, John Wiley & Sons
6. Armstrong, R. A. (1996) *Fault Assessment of a Diesel Engine Using Vibration Measurements and Advanced Signal Processing*. Monterey, CA, Naval Postgraduate School
7. Liu, X., Randall, R. B. and Antoni, J. (2008) Blind separation of internal combustion engine vibration signals by a deflation method. *Mechanical Systems and Signal Processing* **22** (5) 7// 1082-1091
8. Chen, J. and Randall, R. B. (2011) Vibration signal processing of piston slap and bearing knock in IC engines. In: *Surveillance 6* Compeigne, France
9. Chen, J. (2013) *Internal Combustion Engine Diagnostics Using Vibration Simulation*. [PhD Dissertation], The University of New South Wales
10. Beattie, A. (1983) Acoustic emission, principles and instrumentation. *Journal of acoustic emission* **2** (12) 95-128
11. Mba, D. and Rao, R. (2006) Development of Acoustic Emission Technology for Condition Monitoring and Diagnosis of Rotating Machines; Bearings, Pumps, Gearboxes, Engines and Rotating Structures. *The Shock and Vibration Digest* **38** (1) 3-16

12. Sikorska, J. and Mba, D. (2008) Challenges and obstacles in the application of acoustic emission to process machinery. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* **222** (1) 1-19
13. Sikorska, J. Z. (2006) *The application of acoustic emission monitoring to the detection of flow conditions in centrifugal pumps*. University of Western Australia
14. El-Ghamry, M., et al. (2005) Indirect measurement of cylinder pressure from diesel engines using acoustic emission. *Mechanical Systems and Signal Processing* **19** (4) 751-765
15. Kiriya, N. (2001) Statistical Study on Reliability of Ship Equipment and Safety Management–Reliability Estimation for Failures on Main Engine System by Ship Reliability Database System. *Bulletin of the JIME* **29** (2) P64-70
16. Fog, T. L., et al. (1999) *Neural Networks for Signal Processing IX, 1999. Proceedings of the 1999 IEEE Signal Processing Society Workshop*.:Aug 1999
17. Gill, J., et al. (2001) A study of small HSDI diesel engine fuel injection equipment faults using acoustic emission. *Journal of Acoustic Emission(USA)* **18** 211-216
18. El-Ghamry, M. H., Reuben, R. L. and Steel, J. A. (2003) The development of automated pattern recognition and statistical feature isolation techniques for the diagnosis of reciprocating machinery faults using acoustic emission. *Mechanical Systems and Signal Processing* **17** (4) 805-823
19. Frances, A., et al. (2004) Investigation into identification of faults in a small HSDI diesel engine using acoustic emission. In: *DGZfP-Proceedings, BB,*
20. Pontoppidan, N. H., Sigurdsson, S. and Larsen, J. (2005) Condition monitoring with mean field independent components analysis. *Mechanical Systems and Signal Processing* **19** (6) 1337-1347
21. Wu, W., Tan, A. and Kim, E. (2010) Enhancing acoustic emission signals from multi-cylinder diesel engine.
22. Douglas, R. M., Steel, J. A. and Reuben, R. L. (2006) A study of the tribological behaviour of piston ring/cylinder liner interaction in diesel engines using acoustic emission. *Tribology International* **39** (12) 12 / 01 / 1634-1642
23. Douglas, R. M. (2007) *Monitoring of the piston ring-pack and cylinder liner interface in diesel engines through acoustic emission measurements*. [PhD dissertation], Heriot-Watt University
24. Lin, T. R. and Tan, A. (2011) *Proceedings of World Conference on Acoustic Emission-2011*. Vol. 1, Chinese Society for Non-destructive Testing
25. Lin, T. R., Tan, A. and Mathew, J. (2011) Condition monitoring and diagnosis of injector faults in a diesel engine using in-cylinder pressure and acoustic emission techniques. *Dyanmics for Sustainable Engineering* **1** 454-463
26. Lowe, D. P., et al. (2011) Diesel knock combustion and its detection using acoustic emission. *Journal of Acoustic Emission* **29** 78-88
27. Lowe, D. P. (2013) *Characterisation of combustion related acoustic emission sources for diesel engine condition monitoring*. [Dissertation], Queensland University of Technology
28. Robertson, A., et al. (2004) *Proceedings of the 26th conference on acoustic emission testing, EWGAE, Berlin, Germany*
29. Nivesrangsan, P., Steel, J. A. and Reuben, R. L. (2005) AE mapping of engines for spatially located time series. *Mechanical Systems and Signal Processing* **19** (5) 9// 1034-1054

30. Nivesrangsan, P., Steel, J. A. and Reuben, R. L. (2007) Source location of acoustic emission in diesel engines. *Mechanical Systems and Signal Processing* **21** (2) 1103-1114
31. Nivesrangsan, P., Steel, J. A. and Reuben, R. L. (2007) Acoustic emission mapping of diesel engines for spatially located time series—Part II: Spatial reconstitution. *Mechanical Systems and Signal Processing* **21** (2) 2// 1084-1102
32. Nagata, M., et al. (2012) Evaluation of tribological properties of bearing materials for marine diesel engines utilizing acoustic emission technique. *Tribology International* **46** 02 / 01 / 183-189
33. Abdou, W., Balodimos, N. and Reuben, B. (2012) Acoustic Emission in Diesel Engines – Towards a Time Series Model for the Injection Process. In: *Proceedings of the 30th European Conference on Acoustic Emission Testing & 7th International Conference on Acoustic Emission,*
34. Jafari, S. M., Mehdigholi, H. and Behzad, M. (2014) Valve Fault Diagnosis in Internal Combustion Engines Using Acoustic Emission and Artificial Neural Network. *Shock and Vibration* **2014** 9
35. Koike, N., Kumagai, Y. and Nakamura, K. (1998) Development of detection system for abnormal wear of engine bearings. *JSAE Review* **19** (1) 27-32
36. Li, W., et al. (2001) A Study of the Noise from Diesel Engines Using the Indpendent Component Analysis. *Mechanical Systems and Signal Processing* **15** (6) 11// 1165-1184
37. Jiang, J., et al. (2008) Monitoring of diesel engine combustions based on the acoustic source characterisation of the exhaust system. *Mechanical Systems & Signal Processing* **22** (6) 1465-1480
38. Arroyo, J., Muñoz, M., Moreno, F., Bernal, N., Monne´, C. (2013) Diagnostic method based on the analysis of the vibration and acoustic emission energy for emergency diesel generators in nuclear plants. *Applied Acoustics* **74** (4) 502-508
39. Sharkey, A. J., Chandroth, G. O. and Sharkey, N. E. (2000) *Neural Networks, 2000. IJCNN 2000, Proceedings of the IEEE-INNS-ENNS International Joint Conference on*. Vol. 6, IEEE
40. Pontoppidan, N. H. and Larsen, J. (2003) *Neural Networks for Signal Processing, 2003. NNSP'03. 2003 IEEE 13th Workshop on*, IEEE
41. Inayatullah, O., et al. (2010) Development of Acoustic Emission Viscosity Model for Measuring Engine Oil Viscosity Relationship with Engine Oil In-Service Age. *Tribology Online* **5** (6) 255-261
42. Elamin, F., et al. (2010) Diesel engine valve clearance detection using acoustic emission. *Advances in Mechanical Engineering* **2010** 01 / 01 /
43. Elamin, F., et al. (2010) Detection of Diesel Engine Injector Faults using Acoustic Emissions In: *COMADEM 2010: Advances in Maintenance and Condition Diagnosis Technologies towards Sustainable Society,* Nara, Japan
44. Wu, W. (2013) *The detection of incipient faults in small multi-cylinder diesel engines using multiple acoustic emission sensors*. [PhD dissertation], Queensland University of Technology
45. Alam, A. K. (2013) *The detection of adhesive wear on cylinder liners for slow speed diesel engine through tribology, temperature, eddy current and acoustic emission measurement and analysis*. [PhD Dissertation], University of Newcastle Upon Tyne
46. Elamin, F. (2013) *Fault Detection and Diagnosis in Heavy Duty Diesel Engines Using Acoustic Emission*. [PhD disseratation], University of Huddersfield

Appendix A: Summary of Prior Studies

This appendix provides a review of AE engine diagnostic studies reported in the open literature. Small pockets of this work have been undertaken over perhaps the past fifteen years, but a sustained research presence does not appear to have been established anywhere as of this writing. Table 2 gives a chronological summary of these studies.

Fog et al. [16] conducted some of the first reported experimental studies of engine AE measuring an exhaust valve of a large marine diesel in an attempt to detect burn-through, and applying principal component analysis. Gill et al. [17] varied the fuel injector discharge pressure as a fault condition and noted changes in the raw acoustic emission signal. El Ghamry et al. [18] considered the statistical properties of the local rms of the AE signals and found these signals to be sensitive to combustion behaviour. Frances et al. [19] simulated injector faults by altering the injector shim, as well as simulating a manifold gasket leak, then measuring the various characteristics of the AE response to the altered injection and parameters and with the leak, obtaining mixed results on the effectiveness of various parameters. El Ghamry et al. [14] used cepstral methods with acoustic emission measurement to infer cylinder pressure waveforms from the measured AE signals, finding the cepstral analysis to perform well when the AE signal had lower energy content.

Pontoppidan et al. [20] applies a method of independent components analysis (ICA) to detecting faults using rms AE, with a focus more on comparison of methods than specific description of the fault condition. ICA was also used by Wu et al [21] to separate out the AE signal contributions of adjacent cylinders on a four-cylinder engine. Douglas et al. [22] and Douglas [23] measured AE related to the tribological interaction and blowby between piston rings and cylinder liners, noting increased AE with increasing piston velocity. Lin and Tan [24] explored the AE characteristics of a small multicylinder diesel engine and compared this to vibration and pressure traces, and Lin et al. [25] attempted to create an injector fault by grinding down a pintle head, but could not conclusively measure altered combustion characteristics. Lowe et al. [26] induced diesel knock through ethanol fumigation of the fuel and found that while a sensor on the head could not detect the knock condition, a sensor on the block could. Later work by Lowe [27] also found that valve closure with excessive lash clearance to be readily observable in AE, but piston slap was only marginally detectable using a window of AE energy about the expected slap locations.

Sensor placement is important for measuring AE as the stress waves do not travel long distances. However, in the case of engine diagnostics this relieves the challenge of poor signal to noise ratio in vibration signals noted earlier where dynamic phenomena from other components and vehicle motion complicate vibration analysis. Characterization of the AE transmission characteristics through the engine block and representative structures was conducted in a series of papers by Robertson et al. [28] and Nivesrangsan, Steel and Reuben [29-31], which calculated wave speeds and attempted to determine the spatial location of the source based on the arrival times of AE events. Many of these engine AE diagnostic studies are listed in chronological order in Table 2.

Some studies of engine AE diagnostics have been done in rig tests rather than on a running engine.

Nagata et al. [32] measured increased AE in a plain bearing when oil was interrupted, leading to increased asperity contact and bulk failure. Abdou et al. [33] measured AE on fuel injectors on a rig and compared this to measured pressure in the fuel line. Jafari et al. [34] measured AE from leakage flow in simulated cracked and notched valves of a cylinder head from a spark-ignited engine. Additionally, many works as summarized by Mba and Rao [11] have established feasibility and developed methods for fault monitoring of relevant components such as gears and bearings that may be applied to engines as well.

Finally, other works have characterized high frequency acoustic or vibration behaviour of engines, but have been under the roughly 100 kHz lower limit for what is considered acoustic emission in this work. Those studies are relevant to the phenomena measured here and although an exhaustive review of all vibroacoustic approaches to engine diagnostics is beyond the scope of this work, a few are noted here for reference. Using microphone measurements, Koike et al. [35] were able to detect the onset of scuffing when oil was interrupted to an engine bearing, Li et al. [36] applied independent component analysis to acoustic measurements to try to separate various process, and Jiang et al. [37] was able to detect injection pressure and valve timing faults. Arroyo et al. [38] compared simple signal rms of vibration and up to 62.5 kHz to detect a misfiring cylinder. These varied examples support that vibroacoustic methods for detecting and separating specific engine processes and phenomena can be accomplished with a range of instrumentation, although AE generally allows improved diagnosis with a higher signal to noise ratio [23]

The literature shows that some conditions and faults are more readily diagnosed from acoustic emission signals than others, but their versatility along with non-intrusive and relative low cost make them an attractive sensor for engine monitoring. Most of the promising work to date has focused on the operation of the engine top end such as injection, combustion and valve operation.

Table 2 Chronological summary of selected engine AE diagnostic studies

Author	Year	Engine Type or Component Rig	Study summary
Fog et al. [16]	1999	MAN B&W 2-stroke 500 mm bore 4-cyl diesel	PCA approach to detecting valve leakage/burn through
Sharkey et al. [39]	2000	4-stroke 2-cyl diesel, 10.4 kW at 3000 rpm (type not specified)	AE, vibration and pressure sensor fusion diagnostics using neural net
Gill et al. [17]	2001	Perkins 4-cylinder turbocharged T1004-4 HSDI, 135 hp at 2500 rpm	Supply pressure injector faults
El Ghamry et al. [18]	2003	0.5 MW 8-cyl turbocharged SI, and 76 kW 4-cyl HSDI diesel	Statistical properties of AE signals, valve and gasket faults
Pontoppidean and Larsen [40]	2003	Man B&W (unspecified)	Comparison of various PCA/ICA techniques
Frances et al. [19]	2004	Lister-Petter 4X90 HSDI diesel engine, 1000-3000 rpm, 19-33 kW	Supply pressure injector faults and gasket leak
Robertson el al. [28]	2004	MAN B&W 2-stroke diesel, 600 mm bore	wave propagation studies using lead break for AE source identification

Pontoppidean et al. [20]	2005	MAN B&W 2-stroke diesel	BSS/MFICA using AE, fault mode distinguished but not described
El Ghamry et al. [14]	2005	MAN B&W 2-stroke Diesel, and Perkins 4-cylinder 102 hp diesel	Cepstrum of AE for indirect measurement of cylinder pressure
Nivesrangsan et al. [29]	2005	Perkins 74 kW 4-cyl diesel engine, also representative geometries	AE source location using array of sensors, lead break tests, and various geometries
Douglas et al. [22]	2006	MAN B&W 2-stroke 600 mm bore diesel and Perkins 74kw 4-cyl diesel	Piston/ring tribological interactions
Douglas [23]	2007	6 different engines, mostly large 2-stroke marine diesels (also 4-stroke)	Piston/ring tribological interactions and survey of other AE sources
Nivesrangsan et al. [31]	2007	Perkins 74 kW 4-cyl diesel engine, also representative geometries	Geometry effects in AE source location (2nd part)
Nivesrangsan et al. [30]	2007	Perkins 74 kW 4-cyl diesel engine, also representative geometries	comparison of velocity-based and energy-based source location techniques
Inayatullah et al. [41]	2010	1-cyl 4-stroke, water cooled diesel engine	measured AE correlates with engine oil viscosity
Wu et al. [21]	2010	Ford 47 kW four-stroke, 4-cylinder diesel engine	BSS/MFICA of AE to distinguish signals from adjacent cylinders
Elamin et al. [42]	2010	Ford FSD 425 4-cylinder, four-stroke, in-line OHV, DI diesel	Study of exhaust valve clearance
Elamin et al. [43]	2010	JCB 444T2 4-cylinder, four-stroke, 74 kW turbocharged DI marine diesel	Blocked injector to cause misfire in one cylinder and varying fuel supply pressure
Lin and Tan [24]	2011	Perkins 404C-22, 4-stroke, 4-cylinder diesel, 15 kW output	AE and vibration signal comparison across range of loads
Lin et al. [25]	2011	Perkins 404C-22, 4-stroke, 4-cylinder diesel, 15 kW output	Faulty injector, pintle ground down detectable in AE only at full load
Lowe et al. [26]	2011	Cummins 4-stroke, 5.9 L, 6-cylinder turbocharged DI diesel	Detects diesel knock induced by ethanol fumigation
Nagata et al. [32]	2012	Sleeve-on-plate tribometer test	White metal plain bearing liners
Abdou et al. [33]	2012	Fuel injector rig	Initial attempts to correlate AE signal features with an injector pressure
Wu [44]	2013	Perkins 404C-22, 4-stroke, 4-cylinder diesel, 15 kW output	"Semi-BSS" approach to separate signals from various cylinders
Lowe [27]	2013	Cummins 4-stroke, 6-cyl turbo DI diesel, and Perkins 4-cyl 15 kW diesel	AE characteristics of injectors, diesel knock, valve lash settings, piston slap
Alam [45]	2013	Wartsila Sulzer 10RTA84C 55,100 HP at 102RPM	Sensor comparison to detect ring/liner adhesive wear in large diesels
Elamin [46]	2013	JCB 444T2 4-cylinder, four-stroke, 74 kW turbocharged DI marine diesel	Simulation and modeling of piston slap and lubrication, with consideration of injection
Jafari et al. [34]	2014	Cylinder head flow rig	AE resulting from valve leakage flow

DEFENCE SCIENCE AND TECHNOLOGY GROUP DOCUMENT CONTROL DATA			1. DLM/CAVEAT (OF DOCUMENT)		
2. TITLE Acoustic Emission Sensing for Maritime Diesel Engine Performance and Health			3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (U/L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)		
4. AUTHOR(S) Brian Dykas and James Harris			5. CORPORATE AUTHOR Defence Science and Technology Group 506 Lorimer St Fishermans Bend, Victoria 3207 Australia		
6a. DST Group NUMBER DST-Group–TN-1486	6b. AR NUMBER AR-016-487		6c. TYPE OF REPORT Technical Note		7. DOCUMENT DATE May 2016
8. Objective ID AV12877624	9. TASK NUMBER 07/386		10. TASK SPONSOR Future Submarine Program		
13. DOWNGRADING/DELIMITING INSTRUCTIONS To be reviewed three years after date of publication			14. RELEASE AUTHORITY Chief, Maritime Division		
15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT *Approved for public release* OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111					
16. DELIBERATE ANNOUNCEMENT No limitations					
17. CITATION IN OTHER DOCUMENTS Yes					
18. RESEARCH LIBRARY THESAURUS Acoustic emissions, condition monitoring, diesel engine, high frequency acoustic sensing					

19. ABSTRACT

Monitoring and analysis of high frequency acoustic emissions on marine diesel engines may indicate their condition with the aim to increase engine availability and reduce maintenance overheads for Defence. An experimental study was undertaken to evaluate the application of acoustic emission (AE) sensing to the monitoring of both petrol and diesel internal combustion engine operating condition and health. A commercial-off-the-shelf AE monitoring system and a purpose-built data acquisition system were employed in this study, and an array of digital signal processing techniques were drawn from the literature, adapted and applied to this application. Acoustic emission signals from engine-mounted sensors were able to distinguish load conditions and a failing injector, but large increases in big end bearing clearance were not definitely identified from the acoustic emission signals. DST Group recommends that for any subsequent work that the following is considered:

1. Select an overall diagnostic framework (e.g. permanent or temporary, nature of the system being measured, diagnostic method and sensor type),
2. Define a context using a failure modes, effects and criticality analysis (FMECA), and define good AE candidates,
3. Wherever possible characterise AE signatures by constructing simple isolated component test rigs with seeded faults,
4. Apply the technology directly to the engine of interest,
5. Assess the diagnostic performance of various signal processing techniques, and
6. Partner with research institutions with specialist AE knowledge.